Shielding Calculations Used in the Design of the Accelerator Vault for a 200 MeV FEL Facility*

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Introduction

A free electron laser facility (FEL) is currently under development at JLab which will ultimately utilize a 200 MeV, 5mA (1 MW) superconducting and recirculating electron accelerator employing energy recovery techniques. The first phase of this development has been funded. The current development plan for the FEL facility is as follows:

Phase 0	injector test stand	1995 - 96	funded
Phase 1	IR-UV demo (kW scale FEL)	1996 - 98	IR funded
Phase 2	high power upgrades (MW scale FEL)	1998 -	

The limited phase 0 and phase 1 funding available at present must also provide for a civil construction that will be suitable for accommmodating the final phase 2 upgrades. A discussion of the FEL facility and its proposed program has been given by Neil 1996. The many architectural and civil engineering considerations, as well as radiological protection aspects, that went into the final architectural design of the building, are given in a paper by Dunn et al 1996. Figure 1 shows a layout of the accelerator facility within the FEL vault.

Radiation Design Goal

Most institutions require a radiation design goal which results in a proper level of protection for workers and the general public. This goal is generally set well below regulatory limits and takes into account the type of exposed population, the frequency of the exposure and location where the exposure occurs. A further factor in the design goal is that the major portion of the annual worker dose usually arises from maintenance on activated components when the machine is down. Therefore, to increase the annual worker dose from prompt radiation by economizing on

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shielding might not be cost effective in the long run. The JLab design goal of 2.5 mSv per calendar year (or approximately 1.0 μSv per hour for a work year) is unlikely to result in a worker dose increment greater than about 1.0 mSv per calendar year.

Beam Loss

Average beam loss conditions during normal operations was estimated (and believed to be conservative) to be 0.1% of maximum beam power (1kW from 1MW). Further because a 1 kW beam loss at any point was considered to be too large to be sustained and would also result in excessively thick shielding, it was considered appropriate to average the 1 kW beam loss spacially by assuming a line source along the 60 m length of the accelerator vault. This resulted in a loss term of 15 W/m. It was also necessary to consider the consequences of any accidental full beam loss excursions that might occur. Because the accelerator uses energy recovery, any beam loss will result in a reduction in energy recovered, hence, for a full beam loss event the maximum power loss approximates to the installed RF power, or somewhat less than 100 kW.

Radiation Shielding Methods

The earth berms all round the sides of the partially below grade facility provided excellent shielding for the intense bremsstrahlung beams which extend azimuthally from the plane of the recirculation. Because the building is located partially below grade with the experimental area located on top of the accelerator vault, we were required to specify the thickness of the floor/ceiling shielding using an accelerator beam line to exposure position distance h, of 5 m. Reducing the civil construction to a simple slab shielding case permits the use of straightforward and rapid analytical shielding methods. For a line source we use the familar Sievert type integral. To derive a suitable recipe for this calculation we examined published work as well as conducting studies using Monte Carlo methods. For neutron shielding we considered the parameters presented by Sullivan 1992, who had made measurements and studies of neutron shielding down to energies approaching 100 MeV and the shielding expressions used in the recent shielding code SHIELD-11 used by SLAC (Jenkins 1979). The SLAC code utilises some of Sullivan's source terms for lower energy electron beams but with different relaxation lengths. In order to utilize Monte Carlo transport code methods it is necessary to have an "event" generator to represent the random production of neutrons at the different energies in the neutron spectrum. For electron beams of 200 MeV the event generator PICA is the earliest and most well known (Gabriel et al. 1969). However, due to problems with running this event generator recourse was made to parameterizations of the angular energy spectra based on PICA (Gabriel 1969). This spectrum was randomly sampled and used as input for the Monte Carlo code MARS12 (Mokhov 1989). This spectrum is further discussed below in considering neutron transmission through waveguide penetrations. Additionally the event generator DINREG currently under development was used in conjunction with the transport code system, GEANT (see Degtyarenko 1995 for discussion). The parameters resulting from these methods, together with the external neutron dose rates obtained for the proposed shield thicknesses are presented in table 1.

Table 1. Lateral Neutron Shielding Calculations for Slab Shields

neutron energy (MeV)	source term (Sv m² [kWh]⁻¹)	relax length λ concr (cm)	shield thicknsss t concr (cm)	dist h (m)	beam loss (Wm^{-1})	H_h ($\mu Sv\ h^{-1}$)	totals ($\mu Sv\ h^{-1}$)	equiv pt loss (W)	reference
<25	10	18	220	5	15	0. 1			Sullivan 1992
25 - 100	0.3	28	220	5	15	0. 3			
>100	0.0042	50	220	5	15	0.17	0.6	64	
GRN	9.5	12.8	220	5	15	0.001			SHIELD 11
MID	0.32	23.4	220	5	15	0.06			
HEN	0.0067	51	220	5	15	0. 3	0.3	76	
>15	0.36	33	220	5	15	1.2	1.2	67	MARS12/Gabriel
>0.1	0.288	31.74	220	5	15	0.7	0.7	66	GEANT/
>20	0.23	32.84	220	5	15	0.8	0.8	67	DINREG

For photon radiation shielding we pursued a similar process of examing published data but in this case because of the importance of the forward bremsstahlung spike we included the beam end-on situation. In addition to published data we investigated comparable shielding models using the Monte Carlo codes EGS4 (Nelson 1985) and MARS12. The results are presented in table 2.

It is recognized that local shielding is particularly effective for photon sources and that as little as 4 inches of steel will reduce equilibrium dose rates by a factor ten. For this reason we adopted the less conservative source term used in SHIELD-11 but used it in conjunction with the longer relaxation length which was determined using EGS4 and which also corresponded rather well with other published values. For the prescribed lateral shielding, the neutron and photon radiation sources result in approximately the same external dose rates.

Table 2. Photon Shielding Calculations for Slab Shields (Lateral and End-On)

config	source term (Sv m^2 [kWh]$^{-1}$)	relax length iron (cm)	relax length concr (cm)	shield thcknsss concr t (cm)	dist h (m)	beam loss (Wm^{-1})	H_h (μSvh^{-1})	equiv pt loss (W)	reference
lateral	50	4.7	21	220	5	15	3.1	55	Sullivan
end-on	6 10^4	4.7	21	350	12.5		1.1		1992
lateral	10 to 20 50^a	4.7	20.2	220	5	15	0.4 - 0.8	54	Swanson 1979
end-on	6 10^4	4.7	20.9	350	12.5	50W	0.9		
lateral	11	4.3	17.9	220	5	15	0.1	51	SHIELD
end-on	6 10^4	4.3	17.9	350			0.06		11
lateral	24	4.4	26^b	220	5	15	1.3	55	NCRP
end-on	6 10^4	4.4	20.8^c	350	12.5	50W	0.9		1977
end-on^d	1.1 10^6		20.5	350	12.5	50W	14		EGS4
							(Sv/h)^f		
end-on^d	(1.2 10^6)		(20.5)	100	13.0	50W	2.75		MARS12
end-on^e	(1.1 10^5)		(20.5)	100	13.0	50W	0.25		

(a) value recommended by Swanson.
(b) prescribed to be used for the initial power of ten reduction.
(c) for subsequent thicknesses (note - the numbers given in the table are e-folding and not TVL's).
(d) the model used was that the beam would strike a thin piece of iron (1 X_o) and then the concrete shielding.
(e) for this model a 10 cm Fe target was used prior to the concrete wall.
(f) these dose rates were obtained for the conditions specified, the source term, in brackets, was derived using assumed relaxation length also in brackets.

From consideration of the data and results presented in tables 1 and 2, we established the following shielding recipes:

for shielding:	(Sv m^2 [kWh]$^{-1}$)	$\lambda_{concrete}$ (cm)
neutron	0.3	32
lateral photon	11	21
end-on photon	5 10^4	21

The resultant thicknesses of concrete equivalent shield were specified as: ceiling/roof 2.2 m and vault - east wall 3.5 m.

Waveguide Penetrations

Waveguide penetrations often present problems because of the need for them to be close to the accelerator cavities and, there is also the difficulty with inserting waveguides inside penetrations that incorporate bends to reduce radiation transmission. Many penetrations such as cable ways can be stuffed with suitable material such as sand, but hollow waveguides must of necessity remain empty. The waveguide penetration design for the FEL is illustrated in the geometry shown in figure 2. The overall thickness of the ceiling/floor is 2.44 m rather than 2.2 m because the structure comprised layers of sand for cost saving so the overall density reduction was compensated for by additional thickness. A cautionary word by Chilton et al. 1984, that the analytical treatment of multiple legged ducts is beyond the scope of their book on shielding warns us about the difficulty of achieving a solution using simple methods, nevertheless, as an interesting exercise we attempted an analysis of this waveguide penetration by simple currently available analytical methods and then used the more appropriate Monte Carlo methods for neutron transmission. Efforts were focussed on neutron transmission studies for the same reasons given for the slab shielding and, further, photon transmission seldom results in a dose rate higher than for the neutron dose.

Method 1 (Maerker et al. 1967). Practical examples of the use of this method are detailed in NCRP 1979 and also Chilton 1984 discusses the technique and suggests that it can also be used for fast neutron fluences.

Method 2 (universal curves). A simple way of applying this technique is to derive an entrance dose to the penetration and applying the universal curves for off-axis sources for the initial and subsequent legs of a labyrinth. A convenient way of applying these curves is to use Stevenson's parameterizations (Stevenson 1987). The starting point for both these methods is the neutron source term; 10 Sv $h^{-1}kW^{-1}m^2$ and 10^{12} n cm^{-2} s^{-1} kW^{-1}.

With regard to the Monte Carlo method we utilize a neutron spectrum which extends well below the 15 MeV cut-off for the spectrum derived by Gabriel 1969. This we have done by extending the spectrum to lower energies by fitting Gabriels spectrum piecewise to a Maxwellian using a $1/E^n$ spectrum to link the two parts. The differential energy spectrum on integration was made to fit the source terms given above. The spectrum from Gabriel's work was chosen to cover the whole 0 - 180 degree production angles and as an approximation was taken to be isotropic for the angles lateral to the beam direction. The following expression describes the spectrum:

$$\frac{dn}{dEd\Omega} = 2.2654\times 10^{-3}\left[a\frac{E}{0.7^2}\exp\left(-\frac{E}{0.7}\right)+b\frac{1.298868}{E^{2.4}}\right]+c\frac{1}{E_0}\exp\left[\sum_{j=0}^{v}a_j\left(E/E_0\right)^j\right]$$

(n sr^{-1} MeV^{-1} $elec^{-1}$)

where E_0 is electron beam energy and a_j are the fitting coefficients given by Gabriel (1969):

a_0	a_1	a_2	a_3	a_4	a_5
-5.219050	-29.523773	79.900804	-106.471730	-28.743927	82.589645

Because the equation is a piecewise fit the value of a, b and c are zero except in the neutron energy ranges, E, as follows: 0.1 MeV to 2.38 MeV (a=1); 2.38 MeV to 15 MeV (b=1); 15 MeV to 135 MeV (c=1). This spectrum is compared with a spectrum derived for the same beam conditions and production angles using the event generator DINREG and the result is shown in figure 3. In order to speed the process of randomly sampling the spectrum a data file was created which permitted neutron energies to be randomly sampled using simple linear interpolation.

Two geometries were were adopted. Each geometry comprised two separate sets of conditions - a high energy part of the spectrum (15 - 135 MeV) and a low energy part (0.1 - 15 MeV) in order to improve the count rate for the given energy region. Overall precision can be regarded as 20% - 30%. Geom 1 - In this case the production angles were constrained to direct particles directly at the inside opening of the waveguide penetration and only neutrons exiting the opening at the top were scored, hence any particles that scattered to the top would represent the transmission of the penetration. The result of this run showed that the major fraction of the dose at the top of the penetration was due to incident neutrons of energy less than 15 MeV. The result was also a factor 10 greater than the result obtained using the conventional analytical methods. Geom 2 - In this case the incident neutrons were directed over the ceiling in which the penetration was located. Again only neutrons exiting the hole were scored. This time the contribution to the neutron transmission included particles entering through part of the shielding around the penetration which resulted in a much higher dose at the waveguide opening. The contibution from the high energy part of the spectrum was very much larger than was obtained in the first run. Runs were performed using DINREG/GEANT but using the full 4π yield at the source and also included the thermal neutron contribution.

The results for the waveguide calculations are given in table 3.

Table 3. Results of neutron transmission calculations for waveguide penetrations

method	spectr.	dose rate (μSv[kWh]$^{-1}$)	dose rate (μSv[kWh]$^{-1}$)
method 1 (Maerker et al.1967)		4.0	totals for m/c methods
method 2 (universal curves)		6.0	
m/c method - run 1 neutrons	high en	1.1	
directed at hole	low en	47	48.1
m/c method - run 2 neutrons	high en	188	
directed over ceiling	low en	107	295
m/c method - DINREG/GEANT		270	270

The design of the penetration was considered satisfactory on the basis of the design 50 W point loss equivalent. Dose rates of about 15 μSv per hour just at the opening of a waveguide penetration for the worst possible case should not give problems because the waveguide opening is rather small and would only be a local high spot easily avoided or shielded. It is of interest that the result showed that a major part of the dose associated with the waveguide resulted from shield thinning and not transmission through the whole length of the penetration, further, the MC results gave a factor of about 50 times higher than from the simple methods. The total transmission given by the PICA/MARS method and also with DINREG/GEANT was approximately 0.3 mSv [kWh]$^{-1}$.

Access Way Labyrinths

The design of the building constrained the normal access way and emergency exit to four leg labyrinths. The transmission of these labyrinths could not be studied simply using Monte Carlo methods because of low event rates and, inspection of the drawings was sufficient to suggested that the labyrinths would be perfectly adequate from a radiation transmission standpoint. Using the universal curves for neutron transmission and the method for photons given in NCRP 1979 we find transmission factors well able to cope with the neutron source and the forward bremsstrahlung spike which can be traced from the nearest azimuthal loss points.

Conclusions

The paper describes the methods used to specify the shielding for a proposed 200 MeV accelerator intended to produce FEL beams for industrial and research purposes. The azimuthal shielding for most of the accelerator was provided by earth berms, at the East entrance a thichness of wall was specified for shielding the intense forward photon spike. The roof shielding was specified for both lateral neutron and photon sources using a line source. Most of this design work was done using recipes that could be obtained from published material. However, in the case of the waveguide penetrations recourse was made to the use of Monte Carlo methods. Such methods for determining neutron transmission have not been readily available in the past due to the lack of a suitable event generator. The present work was done using a modified PICA spectrum and also the event generator DINREG. It is of interest that typical analytical approaches gave much lower dose rates than was obtained by MC methods, therefore it is concluded that the use of simple methods for determining the radiation transmission of shield penetrations should be treated with caution. The access labyrinths were specified using the analytical methods because of the difficulty of performing MC calculations on such a complex and extended geometry, the use of four leg labyrinths provided considerable safety margins and, even with the reservations expressed above about the use of simple methods, should be adequate.

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Figure 1. Layout of FEL Accelerator in the Accelerator Vault

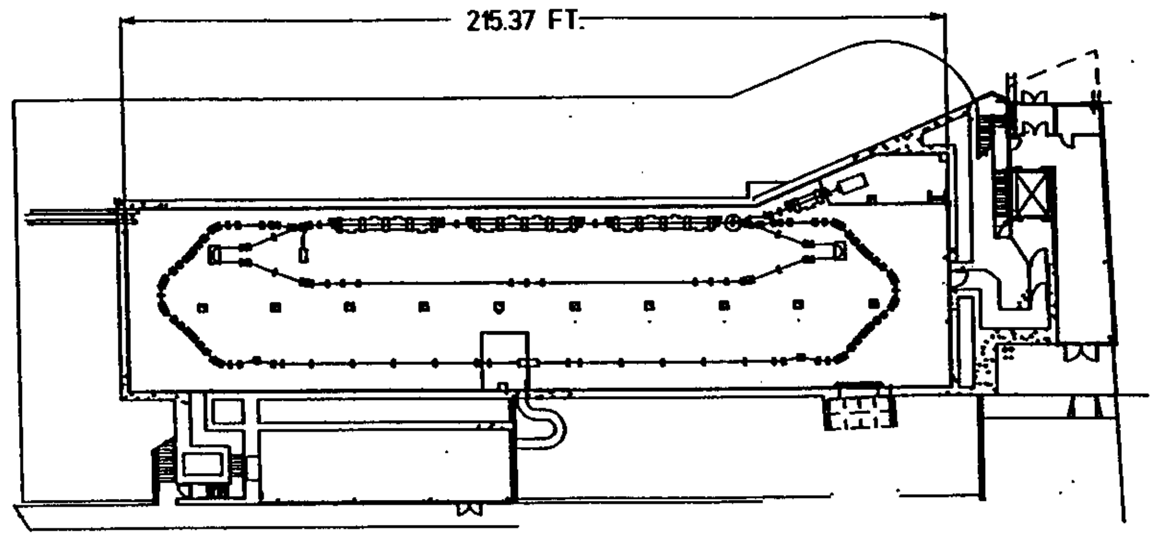

Figure 2. Geometry Used for the Waveguide Penetrations

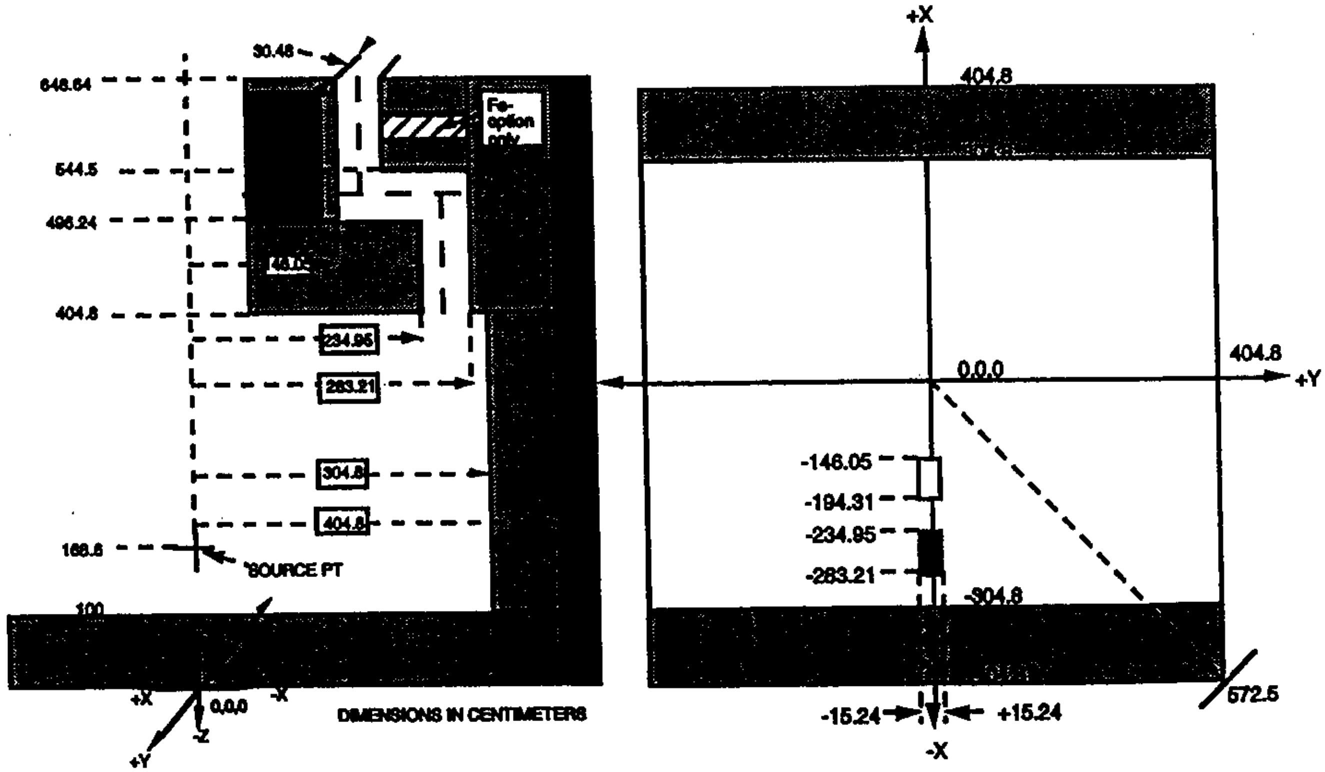

Figure 3. Differential Energy Spectra - DINREG and extended PICA